



Development of an Interoperable GNSS Space Service Volume

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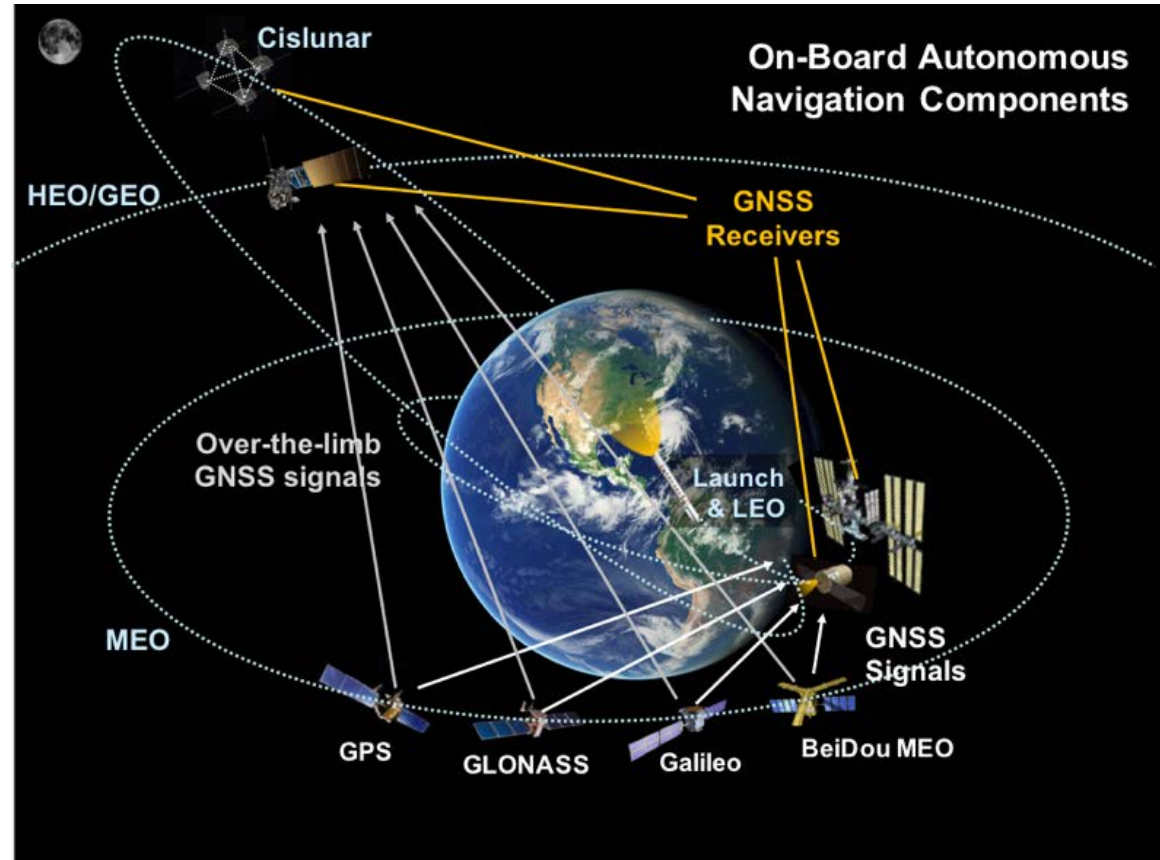
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Space Uses of Global Navigation Satellite Systems (GNSS)

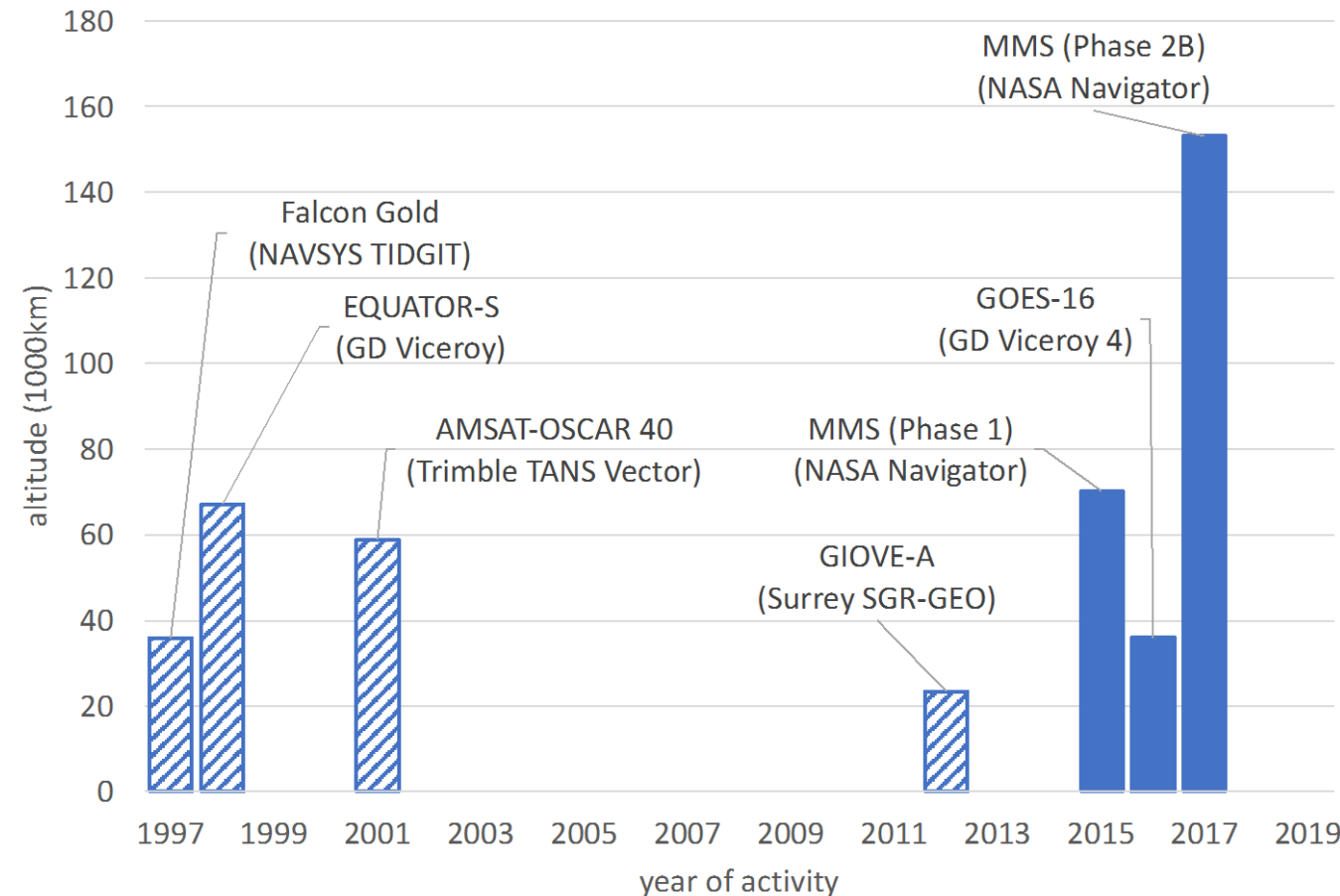
- **Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences:** Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops:** Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination:** Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization:** Support precise time-tagging of science observations and synchronization of on-board clocks



GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

High-Altitude GPS

- 1990s: Early flight experiments demonstrated basic feasibility – Equator-S, Falcon Gold
- 2000: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- 2001: AMSAT OSCAR-40 mapped GPS main and sidelobe signals (Davis et al. 2001)
- 2015: MMS employed GPS operationally at 76,000 km and recently 150,000 km
- 2016: GOES-16 employed GPS operationally at GEO



International Committee on GNSS (ICG)



- The UN International Committee on GNSS (ICG) brings together all six GNSS providers (China, Europe, India, Japan, Russia, & USA) and other voluntary participants to:
 - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
 - Encourage compatibility and interoperability among global and regional systems
- Most recent meeting: ICG-12, Kyoto, Japan
- Next Meeting: ICG-13, X'ian, China

WG-S: Systems, Signals and Services

Major topics include:

- Spectrum compatibility
- Interference detection & mitigation
- Service interoperability
- Performance standards & monitoring

WG-B: Enhancement of GNSS Performance, New Services and Capabilities

Major topics include:

- Development of interoperable multi-GNSS SSV
- GNSS-hosted search-and-rescue payloads
- Space weather and ionosphere modeling

WG-D: Reference Frames, Timing and Applications

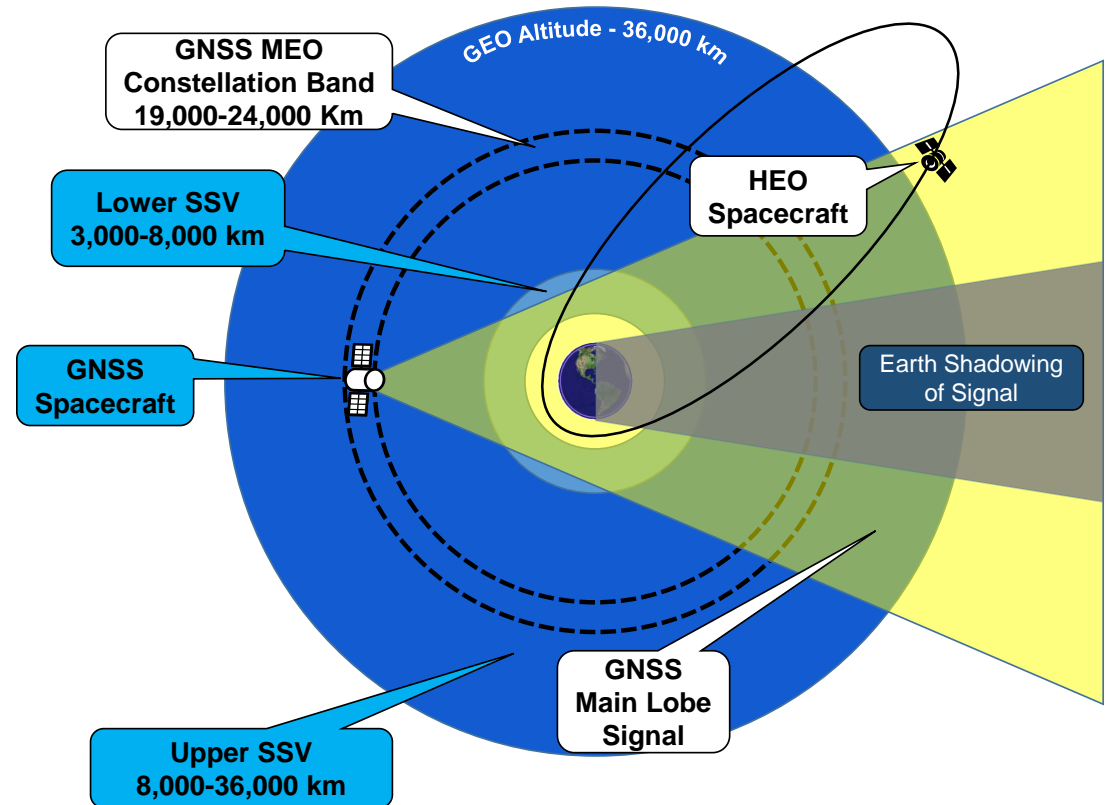
Major topics include:

- ITRF, geodetic reference frame interoperability
- Time standards & multi-constellation offsets
- Constellation orbit modeling & technical data

* Also: WG-C: Information Dissemination and Capacity Building

The Multi-GNSS Space Service Volume

- Two components:
 - Lower SSV (3,000 km–8,000 km)
 - Upper SSV (8,000 km–36,000 km)
- Three performance metrics:
 - Pseudorange Accuracy
 - Signal Availability
 - Received Signal Power

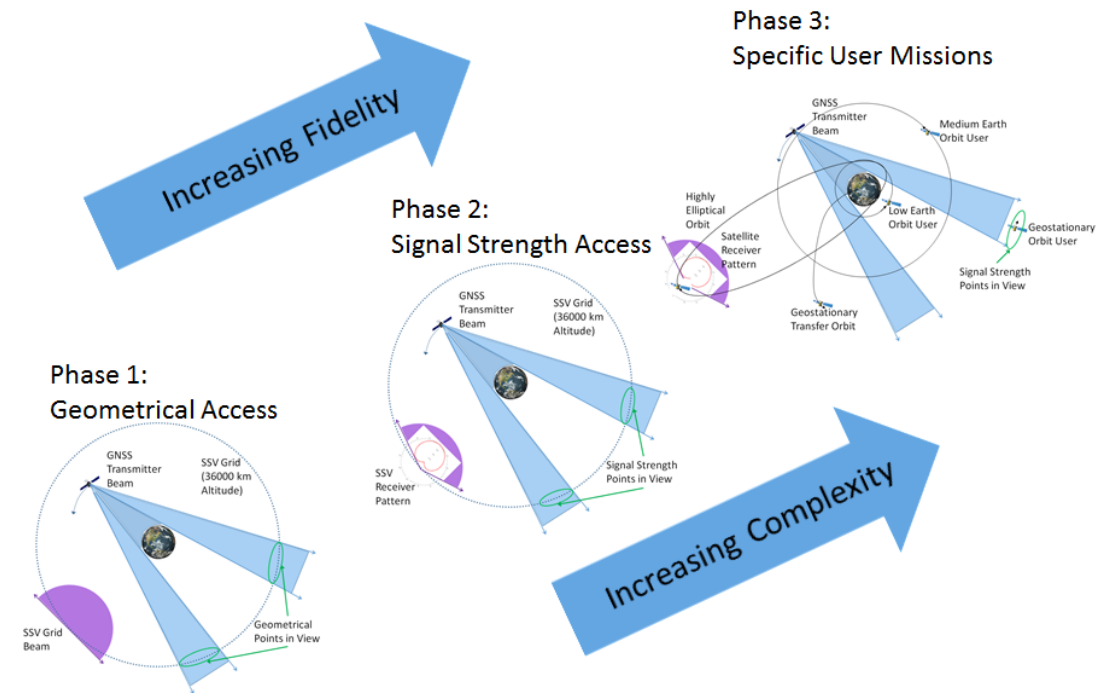


Constellation-Specific Support to SSV

Band	Constellation	Minimum Received Civilian Signal Power		Upper SSV Signal Availability (%)	
		0dBi RCP antenna at GEO (dBW)	Reference off-boresight angle (°)	At least 1 signal	4 or more signals
L1/E1/B1	GPS	-184 (C/A) ¹ -182.5 (C) ²	23.5	80	1
	GLONASS	-179	26	93.9	7.0
	Galileo	-182.5	20.5	64	0
	BDS	-184.2 (MEO) ³ -185.9 (I/G) ⁴	25 19	97.40	24.10
	QZSS	-185.5	22	54	N/A
L5/L3/E5/B2	GPS	-182	26	92	6.5
	GLONASS	-178	34	99.9	60.3
	Galileo	-182.5 (E5b)	22.5	80	0
		-182.5 (E5a)	23.5	86	0
	BDS	-182.8 (MEO)	28	99.90	45.40
		-184.4 (I/G)	22		
	QZSS	-180.7	24	54	N/A
NavIC	-184.54	16	36.90	0.60	
¹ L1 C/A signal					
² L1C signal					
³ Medium Earth Orbit satellites					
⁴ Inclined geostationary (I) and geostationary (G) satellites					

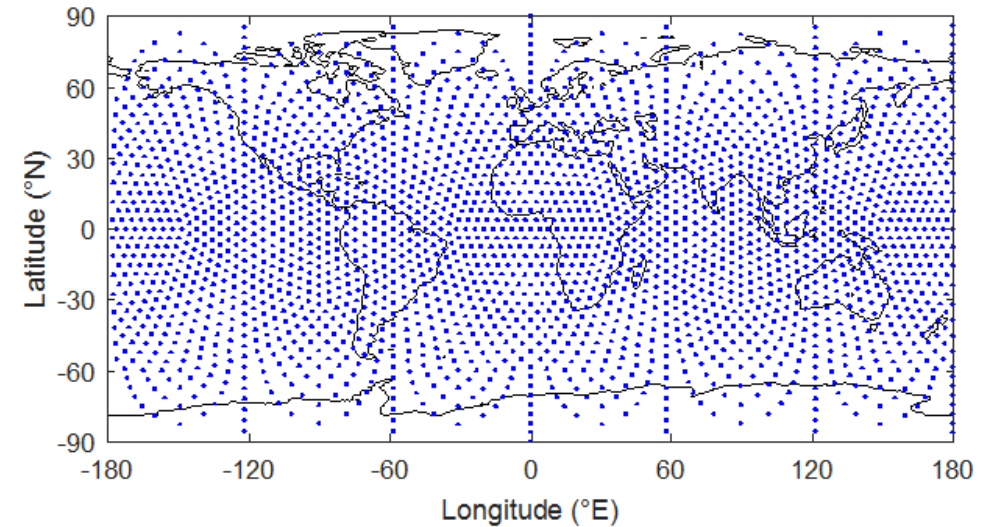
Performance Estimates

- Two types of analysis were performed over three phases:
 1. Global performance analysis
 2. Mission-specific performance analysis, consisting of:
 - GEO case
 - HEO case
 - Lunar case
- Phase 1 & 2 were focused on global analysis
- Phase 3 was mission-specific analysis



Global Performance

- Analysis performed to estimate signal availability on global grid of points (see right)
- Each grid point assumed to be stationary receiver with 0dBi antenna
- Results show improvement in Upper SSV:
 - 1+ signals: 94% -> 99.9%
 - 4+ signals: 7% -> 89.8%



Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%) ¹	MOD (min) ²	Avail. (%) ¹	MOD (min) ²
L1/E1/B1	Global systems	78.5–94	48–111	0.6–7	*
	QZSS	0	* ³	0	*
	Combined	99.9	33	89.8	117
L5/L3/E5a/B2	Global systems	93.4–99.9	7–*	4.2–60.3	218–*
	Regional systems	1–30.5	*	0–1.5	*
	Combined	100	0	99.9	15

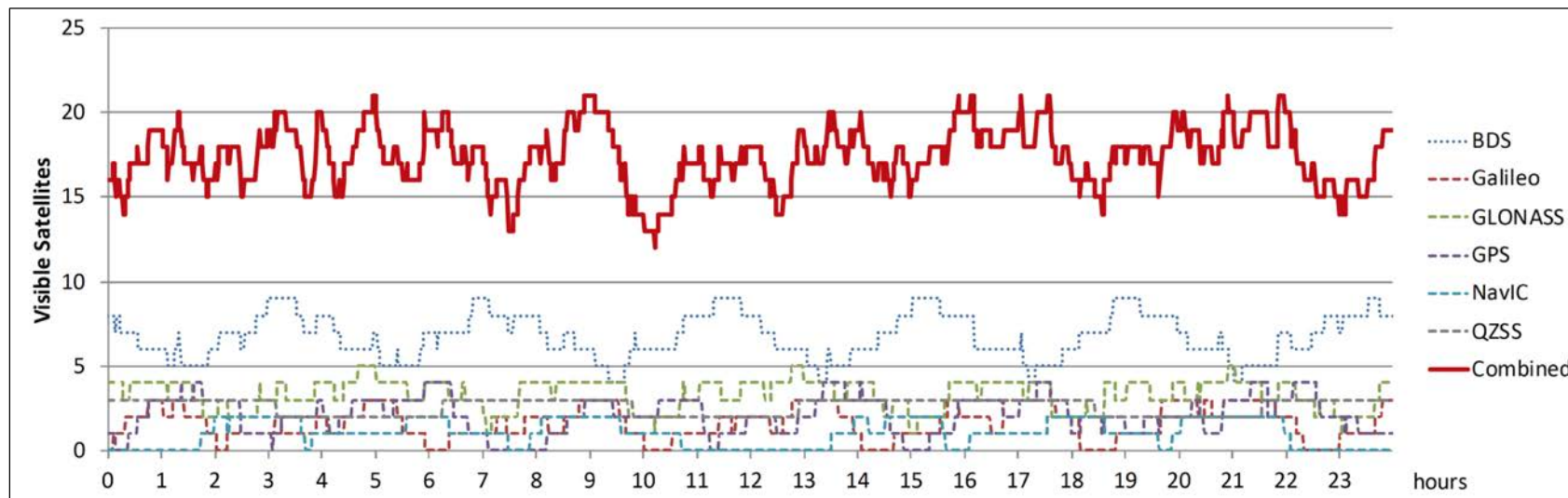
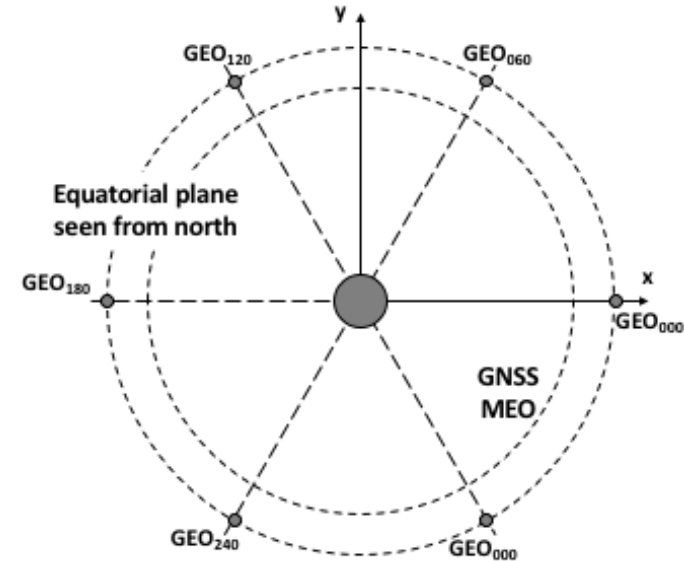
¹average across all grid locations

²at worst-case grid location

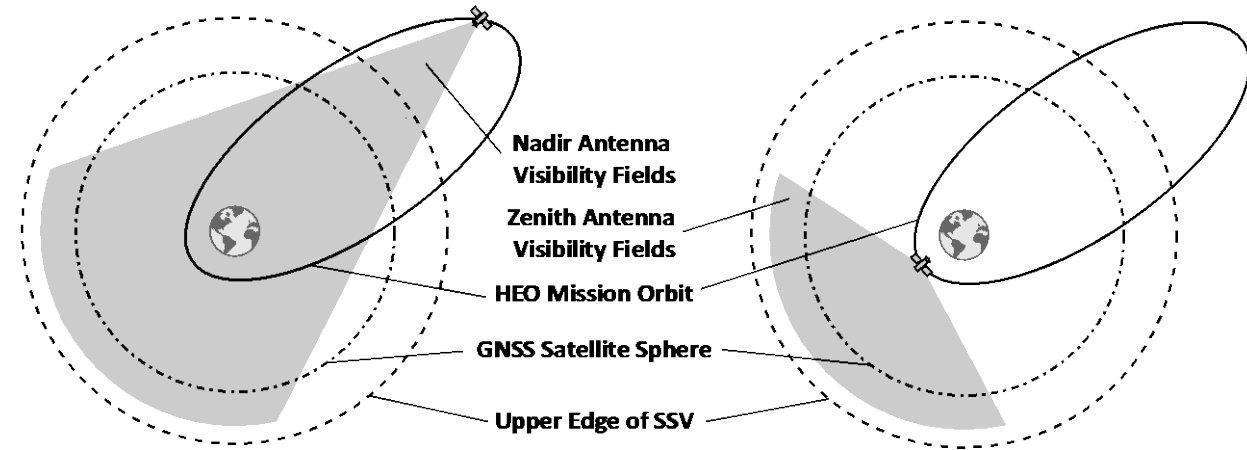
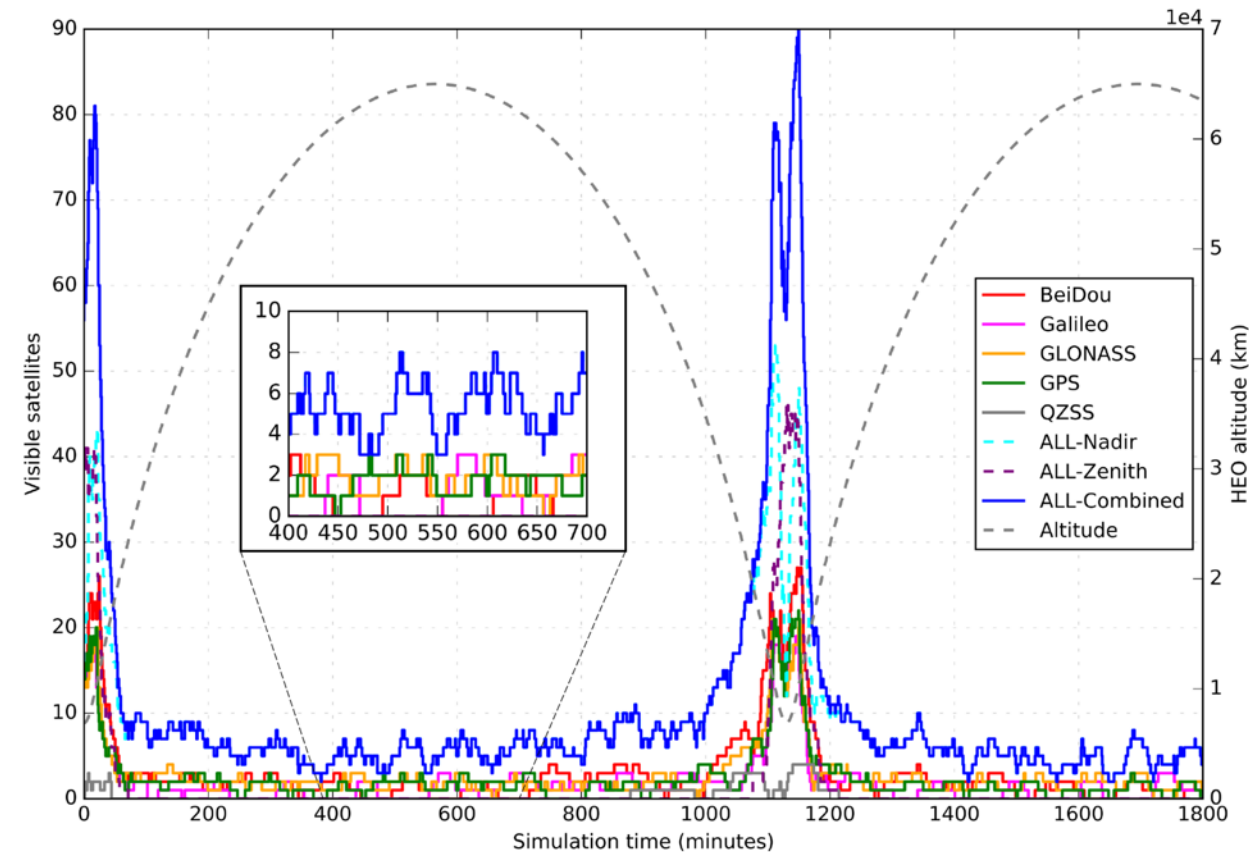
³no signal observed for the worst-case grid location for full simulation duration

GEO Performance

- Mission-specific analysis at six GEO locations (see right)
- Each satellite simulated with realistic high-gain nadir-pointed antenna
- Results (below) show drastic improvement from any individual constellation to all combined
- Visibility variable with location around GEO belt



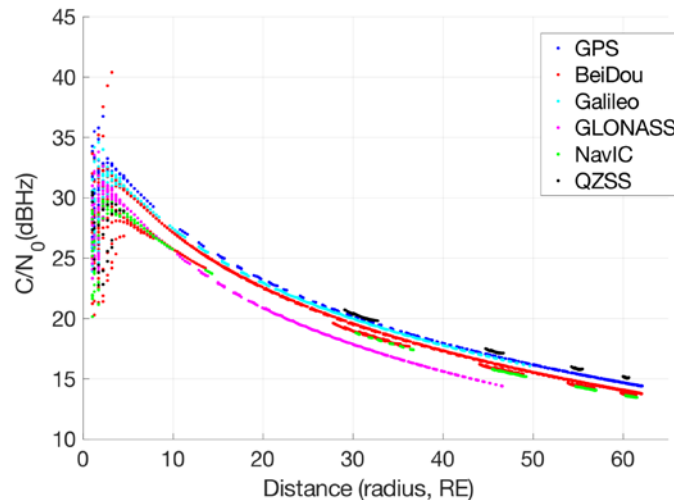
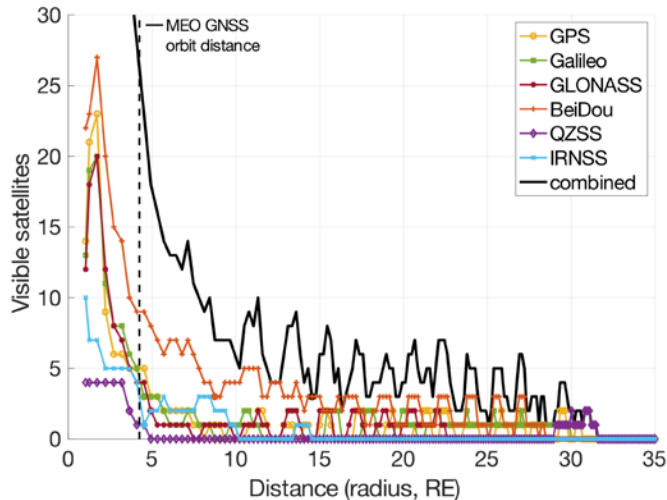
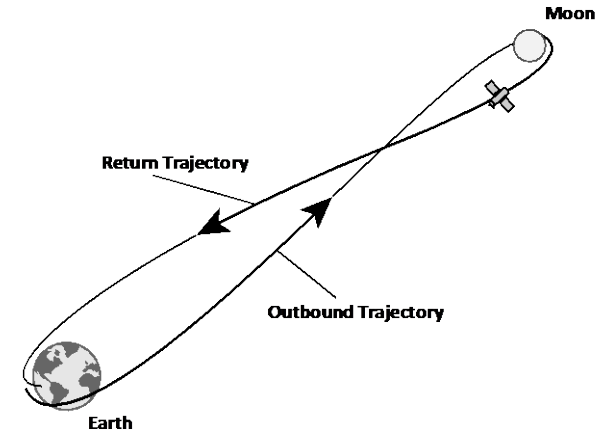
HEO Performance



- Mission-specific analysis of example highly-elliptical science mission
- User satellite modeled with both nadir-pointed and zenith-pointed antennas (see figure above)
- Results (left) show improvement when all constellations are used together
- 100% coverage with multiple-satellite visibility is possible even at apogee with all constellations

Lunar Performance Simulations

- Mission-specific analysis of example lunar outbound trajectory
- User satellite modeled with both nadir-pointed and zenith-pointed antennas
- Results (below) show two key features:
 - Overall visibility is split into low-altitude regime with 100% 1+ visibility under approx. 30 RE, and zero-visibility high-altitude region
 - With moderate user equipment improvements, visibility can be achieved all the way to lunar distance



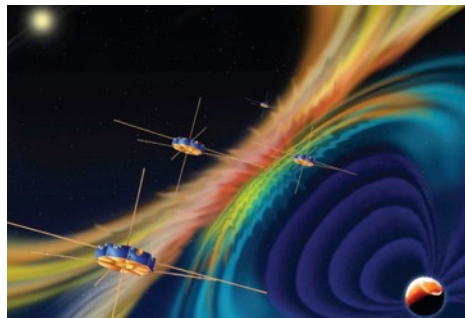
Benefits of Real-Time GPS Navigation in the SSV

Benefits of GPS use in SSV:

- Supports **fast trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- GPS timing **reduces need for expensive on-board clocks** (from: \$100sK-\$1M to: \$15K-\$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to \$500-750K/year)
- Enables new/enhanced capabilities and better performance for **High Earth Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions**, such as:



Earth Weather Prediction using
Advanced Weather Satellites



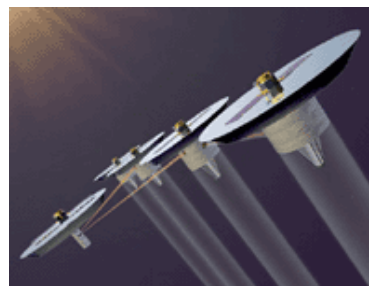
Space Weather Observations



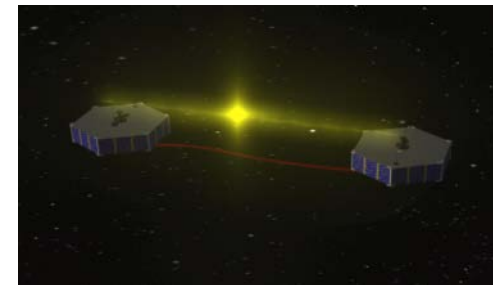
Precise Relative Positioning



Launch Vehicle Upper Stages
and Beyond-GEO applications



Formation Flying, Space Situational
Awareness, Proximity Operations



Precise Position Knowledge
and Control at GEO

SSV: Future Civil Applications

- Earth Weather Missions
 - Objectives: Improve weather forecasting from 3-5 days to 5-7 days; protecting people and property through early warning of tornados, flash floods, and wildfires
 - Role of the SSV: Accurate orbit prediction (position and velocity), fast recovery from trajectory maneuvers, navigation stability to prevent internal image and image to image pixel, and timing
- Space Weather and Heliospheric Science Missions
 - Objectives: Enable High Earth Orbit and Cislunar observations of the magnetosphere to improve understanding of space weather and to potentially start space weather prediction.
 - Role of the SSV: Improved navigation performance (e.g. 10-meter to 1-meter class) and fast recovery from trajectory maneuvers (minute class) for accurate placement of space weather phenomenon; improved operations cadence and increased satellite autonomy to support constellation or formation flying missions; Precise timing enabling lower cost clock alternatives



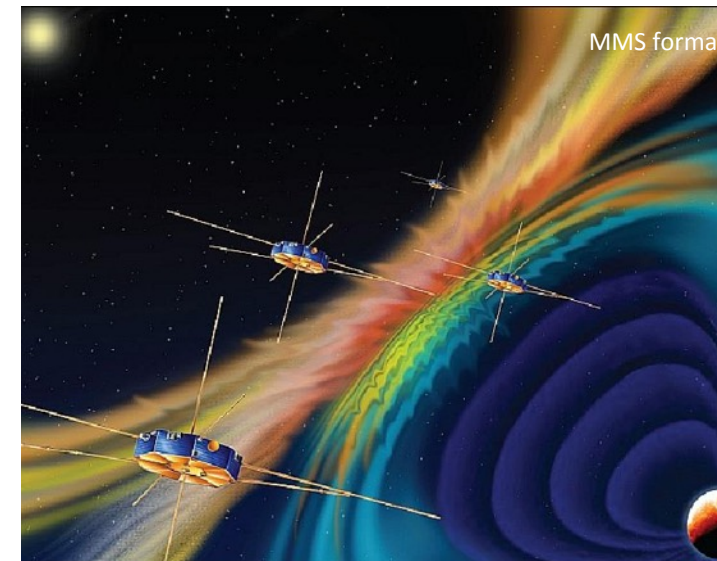
SSV: Future Civil Applications (cont.)

- Satellite Servicing

- Objectives: Extend the lives of satellites through upgrade, repair, refueling, and orbit adjustment; debris removal; in-orbit construction or installation
- Role of the SSV:
 - Fast recovery from trajectory maneuvers required—on the order of minutes during critical rendezvous, proximity operations, and docking
 - Near-continuous GPS signal availability needed to support satellite responsiveness and autonomy
 - Highly accurate absolute orbit state (position and velocity) are necessary to support far-field rendezvous—as a general rule of thumb, position must be known to an accuracy of 10% the inter-vehicle range

- Formation Flying Missions

- Objectives: Enable new classes of missions and new scientific viewpoints through formation flying; spans full spectrum of vehicle sizes (CubeSats to ISS class) and mission orbits (MEO, HEO, GEO, Cislunar)
- Role of the SSV: Precise navigation and timing, fast recovery from trajectory maneuvers, enhanced operations cadence, and increased satellite autonomy. Requirements as low as meter-class navigation in real time, cm-level relative navigation and micro- to nanosecond timing synchronization



SSV: Future Civil Applications (cont.)

- Commercial GEO Missions
 - Objectives: Increase density of the most coveted real estate in space, benefiting commercial and civil space users
 - Role of the SSV: Accurate position and velocity measurements and near-continuous GPS signal availability needed to enable accurate, autonomous vehicle station keeping during near-continuous low thrust maneuvering
- Launch Vehicle Upper Stages & Deep Space Missions, En Route, and Return
 - Objectives: Improve real-time vehicle insertion and trajectory accuracy reducing fuel requirements and improving payload mass capacities
 - Role of the SSV: High accuracy, high cadence position, velocity, and time knowledge to minimize the trajectory propagation errors of the vehicle during flight



SSV: Future Civil Applications (cont.)

- Lunar Missions

- Objectives: There is a renewed interest in the moon as a target for rovers, landers, and human exploration. The US plans to return to human exploration of the moon and cislunar space in the next few years with Exploration Missions (EM) 1 and 2. EM-3 may begin construction of a “gateway”—a permanent way-station in the vicinity of the moon for staging deep space activity
- Role of the SSV:
 - GPS can provide measurements for mid-course correction burns during outbound and return cruise
 - Simulations have shown that GPS signal availability can be extended to lunar distances by augmenting existing high-altitude GPS navigation systems (such as MMS) with a high-gain antenna (Winternitz et al. 2017, Ashman et al., 2018)
 - Navigation backup for the crew capsule, Orion, if communications link is lost
 - Lunar platform like the gateway could use GPS for position, velocity, and attitude, as well as a stable and accurate timing source for hosted science and technology payloads



Conclusions

- Use of high-altitude GNSS has expanded significantly, and is now an enabling technology for future missions.
- Through the UN International Committee on GNSS (ICG), all GNSS and RNSS providers have agreed to the Multi-GNSS Space Service Volume, which documents performance expectations above 3,000 km altitude.
- Performance estimates (global and mission-specific) show significantly enhanced signal availability at all altitudes when multiple constellations are used.
- Full results are available in UN SSV Booklet.